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SELF-PUMPED PHOTOREFRACTIVE GRATINGS IN Fe:$KNbO_3$ (PREPRINT)

Dean R. Evans, G. Gook, J.L. Carns, and M.A. Saleh

Hardened Materials Branch
Survivability and Sensor Materials Division

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WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
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DEAN R. EVANS, Ph.D.
Agile Filters Project
Exploratory Development
Hardened Materials Branch

//Signature//

MARK S. FORTE, Acting Chief
Hardened Materials Branch
Survivability and Sensor Materials Division

//Signature//

TIM J. SCHUMACHER, Chief
Survivability and Sensor Materials Division

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Dean R. Evans (AFRL/MLPJ)
G. Cook (Universal Technology Corporation)
M.A. Saleh (UES, Inc.)
J.L. Carns (General Dynamics Information Technology, Inc.)

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Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command, United States Air Force

Universal Technology Corporation
1270 North Fairfield Road
Dayton, OH 45432

UES, Inc.
Dayton, OH 45432

General Dynamics Information Technology, Inc.
5100 Springfield Pike, Suite 509
Dayton, OH 45431

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14. ABSTRACT

- High gain confirmed in off-axis geometries for Fe:$KNbO_3$
- Mismatch between theory and experiment for mid-range crystal angles, especially for the a-c plane
- Large apparent variation in the effective trap density with crystal angle
- Modified theory gives a good fit to experimental data
- Mechanism for trap density anisotropy is unclear

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Self-Pumped Photorefractive Reflection Gratings in $Fe:KNbO_3$

G. Cook[a,b], J. L. Carns[c],

M. A. Saleh[d], D. R. Evans[a]

[a]Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH

[b] Universal Technology Corporation, Dayton, OH

[c]Anteon Corporation, Dayton, OH

[d]UES, Dayton, OH

Outline

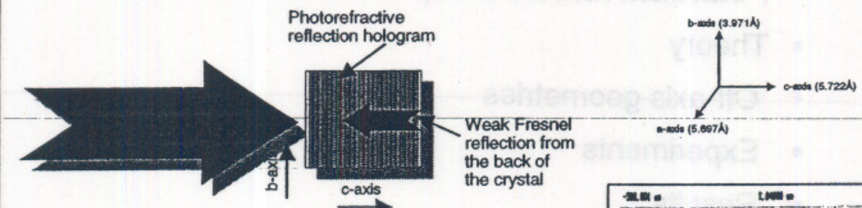
- Potassium niobate as a photorefractive
- Theory
- Off-axis geometries
- Experiments
- Results
- A controversial suggestion……
- Discussion
- Conclusion (confusion?)

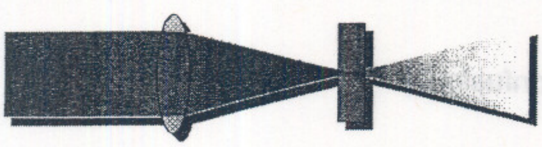
Potassium niobate as a photorefractive

- High trap density
  - ↳ Allows efficient counter-propagating gratings to be written
- High sensitivity
  - ↳ Fast response times
- Broad spectral response
  - ↳ 400nm - ~700nm (with Fe doping)
  - ↳ 400nm - >700nm? (with Ni doping)
- Difficult to grow reproducibly
  - ↳ Program under way to fix this (looks very promising!)

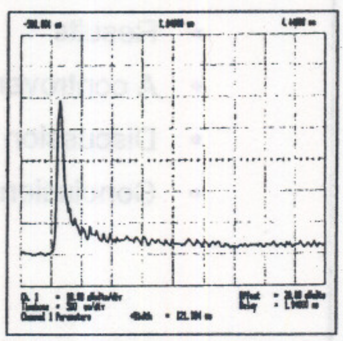
Experiment

- Self-pumped two beam coupling





Focal plane geometry



Theory

- Optical fields
- Intensity fringes

$$\left.\begin{aligned} E_s(z,t) &= \frac{1}{2}A_s(z,t)\exp i(-kz-\omega t)+c.c \\ E_p(z,t) &= \frac{1}{2}A_p(z,t)\exp i(+kz-\omega t)+c.c \end{aligned}\right\} I(z,t)=\left(I_s+I_p\right)\left(1+\frac{A_s A_p^*}{I_s+I_p}\exp\left(2ikz\right)+c.c.\right)$$

$$\frac{dN_d^+}{dt} = s\left(I+I_{Dark}\right)\left(N_d-N_d^+\right)-\gamma_r n N_d^+$$

$$\frac{dn}{dt} = \frac{dN_d^+}{dt}+\frac{1}{e}\frac{dJ}{dz}$$

$$J = e\mu n E_{sc}+\mu k_B T\frac{dn}{dz}+sI\left(N_d-N_d^+\right)e\delta$$

$$\varepsilon_s\frac{dE_{sc}}{dz} = e\left(N_d^+-N_a^--n\right)$$

(Kiev group/Kukhtarev material equations)

$A_{s,p}$ are the slowly varying amplitudes of the electric fields

Theory

- Solving the Kiev group/Kukhtarev's equations for the space charge field gives:

$$\frac{a}{\tau_{di}}\frac{\partial E_{sc}}{\partial t}+bE_{sc}+cm=0$$

- Where:

$$m=\frac{\sqrt{I_s I_p}}{I_s+I_p+I_{Erasure}}\exp\left(-i\varphi\right), \qquad \tau_{di}=\varepsilon_s\gamma_r N_a / e\mu s(I_p+I_s+I_{Erasure})(N_d-N_a)$$

$$a=1+\frac{E_d}{E_m}-i\frac{E_0}{E_m}, \qquad E_d=\frac{2\pi k_B T}{e\Lambda}$$

$$b=1+\frac{E_d}{E_q}-i\left(\frac{E_0+(N_a/N_d)E_{pv}}{E_q}\right), \qquad E_q=(1-N_a/N_d)\,eN_a/2k\varepsilon_s$$

$$E_{pv}=\gamma_r N_a^-\delta/\mu$$

$$c=E_0+E_{pv}+iE_d, \qquad E_m=\gamma_r N_a/(\mu K)$$

Theory

- The space charge field modifies the refractive index through the linear Pockels effect
- Substituting the modulated index into the optical wave equation gives the coupled equations for the intensities and phase:

$$\begin{cases} \dfrac{\partial I_p}{\partial z} = -\alpha I_p - \dfrac{2\pi n^3 r_{eff}}{\lambda}\sqrt{I_p I_s}\,\mathrm{Im}\left(E_{sc}\exp(i\varphi)\right) \\ \dfrac{\partial I_s}{\partial z} = +\alpha I_s - \dfrac{2\pi n^3 r_{eff}}{\lambda}\sqrt{I_p I_s}\,\mathrm{Im}\left(E_{sc}\exp(i\varphi)\right) \\ \dfrac{\partial \varphi}{\partial z} = \dfrac{\pi n^3 r_{eff}(I_p - I_s)}{\lambda\sqrt{I_p I_s}}\mathrm{Re}\left(E_{sc}\exp(i\varphi)\right) \end{cases}$$

Theory

- In steady state the space charge field and coupled equations reduce to:

$$E_{sc}(z) = \frac{-\left(E_0 + iE_d + E_{pv}\right)m(z)}{1 + \dfrac{E_d}{E_q} - i\left(\dfrac{E_0}{E_q} + \dfrac{N_a E_{pv}}{N_d E_q}\right)}$$

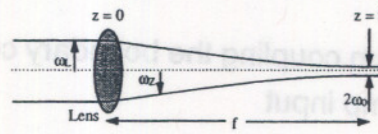
$$\frac{dI_p}{dz} = -\alpha I_p - \Gamma\frac{I_p I_s}{I_p + I_s + I_{Erasure}}$$

$$\frac{dI_s}{dz} = +\alpha I_s - \Gamma\frac{I_p I_s}{I_p + I_s + I_{Erasure}}$$

Where $\Gamma = \dfrac{2\pi}{\lambda} n^3 r_{eff}\,\mathrm{Im}\left(E_s\right)$

Theory

- Focusing



$$\frac{dI_p}{dx} = -\alpha I_p - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}} - \frac{2(z-f) I_p}{z_R^2 + (z-f)^2}$$

$$\frac{dI_s}{dx} = +\alpha I_s - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}} - \frac{2(z-f) I_s}{z_R^2 + (z-f)^2}$$

Theory

- Piezoelectric/photoelastic contributions[1,2]

$$r_{ij}^{eff} = r_{ijk}^{S} \hat{n}_k + p_{ijkl}^{'E} \hat{n}_l A_{km}^{-1} B_m$$

$$A_{ik} = C_{ijkl}^{E} \hat{n}_j \hat{n}_l$$

$$B_i = e_{kij} \hat{n}_k \hat{n}_j$$

r_{ijk}^{S} is the clamped EO tensor

$p_{ijkl}^{'E}$ is the effective elasto-optic tensor

C_{ijkl}^{E} is the elastic stiffness tensor

e_{kij} is the piezoelectric tensor

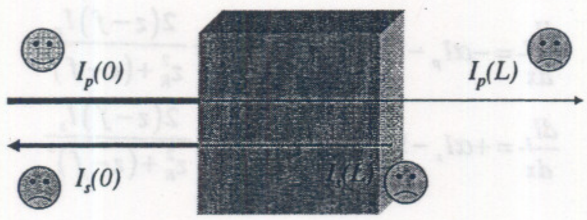
- Scalar effective EO coefficient:

$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$

1) M. Zgonik, K. Nakagawa, P. Günter, "Electro-optic and dielectric properties of photorefractive BaTiO3 and KNbO3", J. Optical Society of America B, vol. 12, no. 8, pp 1416-1421, 1995.
2) M. Zgonik, R. Schlesser, I. Biaggio, E. Voit, J. Tscherry, P. Günter, "Materials constants of KNbO3 relevant for electro- and acousto-optics", J. Applied Physics, vol. 74, no. 2, pp 1287-1297, 1993.

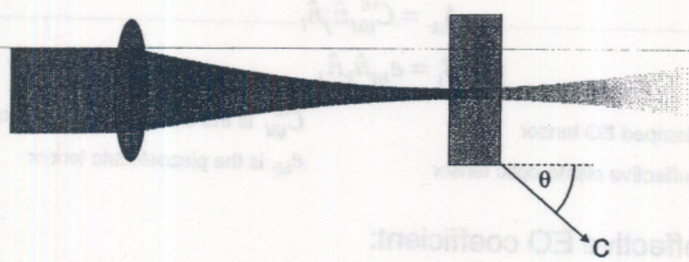
Theory

- No closed form solution to the coupled equations
- Numerical solutions only
- For self pumped two beam coupling the boundary conditions are known only for the pump input
- Iterative shoot and match methods are required



Off-axis concept

- Optical gain is potentially much higher away from the c-axis

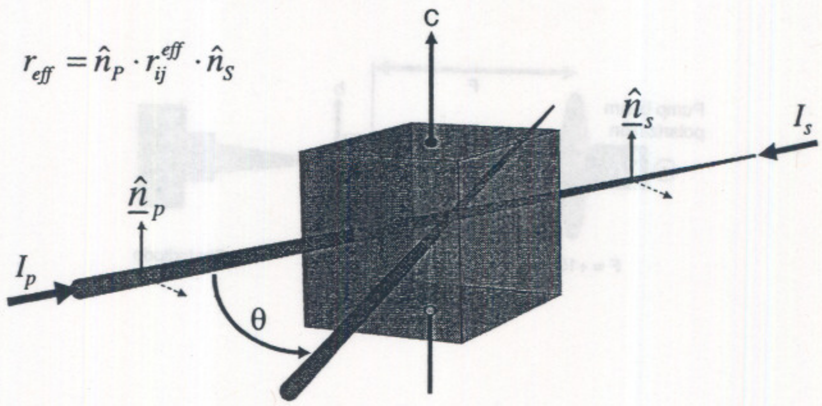


- c-axis is best for $Fe:LiNbO_3$ owing to the huge PV effect
- The same is NOT true for $Fe:KNbO_3$

Off-axis effective electro-optic coefficient

- Beam axis rotation about the c-axis:

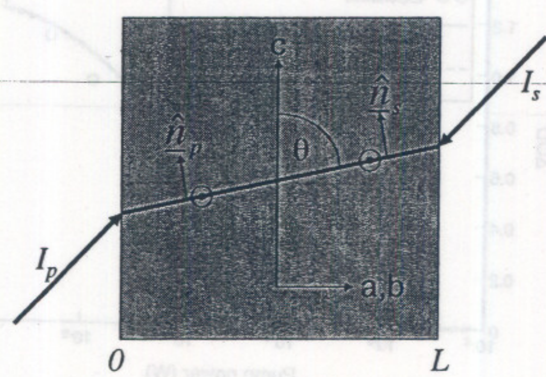
$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$



r_{eff} is <u>zero</u> for all polarizations

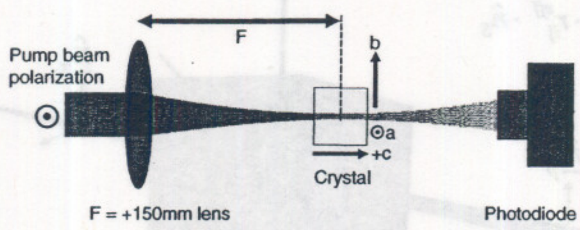
Off-axis effective electro-optic coefficient

- Beam axis rotation in the a-c or b-c planes:

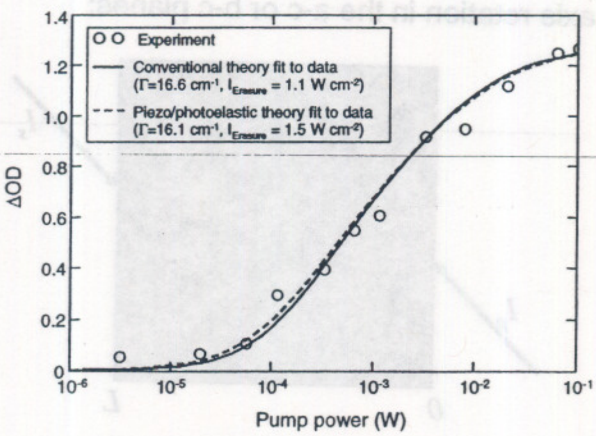


$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$

Determination of Γ and $I_{Erasure}$



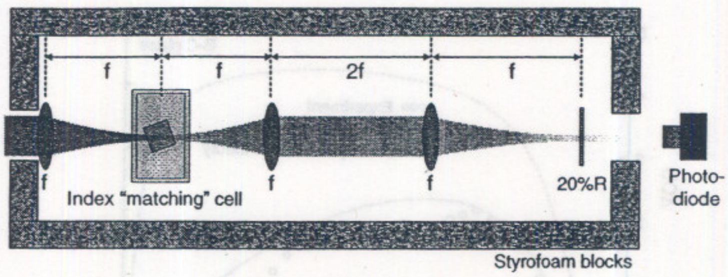
Determination of Γ and $I_{Erasure}$

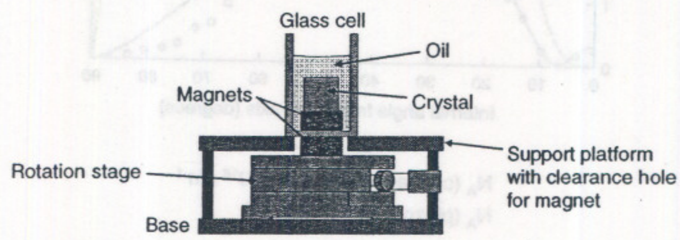


N_A (conventional) = 2.1×10^{16} cm^{-3}
N_A (piezo) = 5.0×10^{16} cm^{-3}

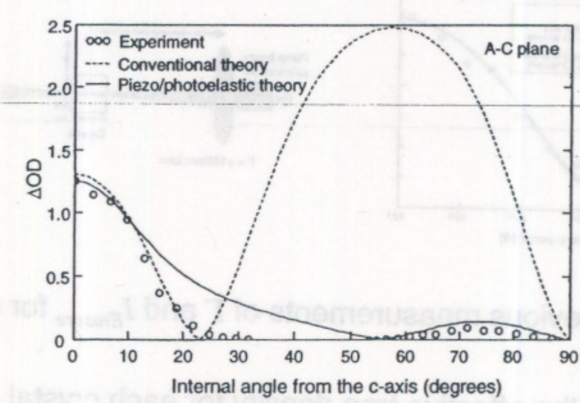
Measuring the off-axis gain in contra-directional Fe:$KNbO_3$

- Experiment:



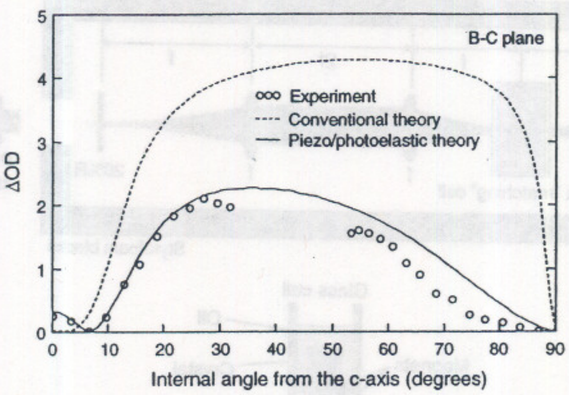


Off-axis gain results



N_A (conventional) = 2.1×10^{16} cm^{-1}
N_A (piezo) = 5.0×10^{16} cm^{-1}

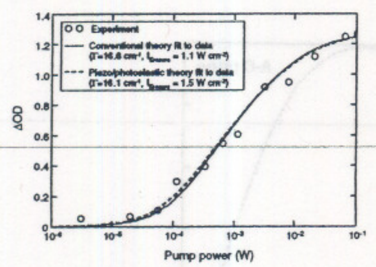
Off-axis gain results

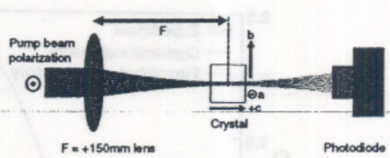


N_A (conventional) = 2.1×10^{16} cm^{-1}

N_A (piezo) = 5.0×10^{16} cm^{-1}

A controversial suggestion....

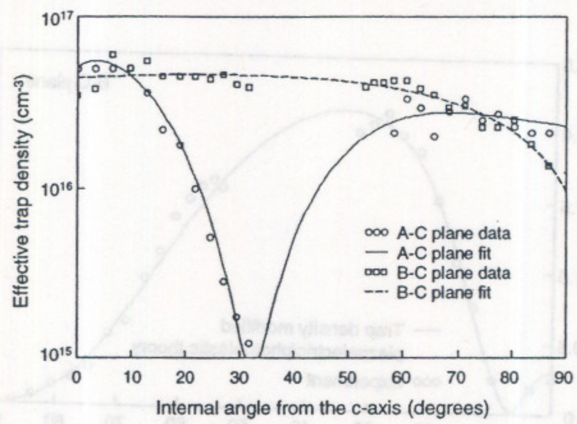




- Repeat previous measurements of Γ and $I_{Erasure}$ for all crystal angles
- Calculate the effective trap density for each crystal angle

"Conventional" transmission/reflection grating method cannot be used reliably for trap density measurements owing to admittance angular restrictions at large crystal angles and competition from rear Fresnel reflection.

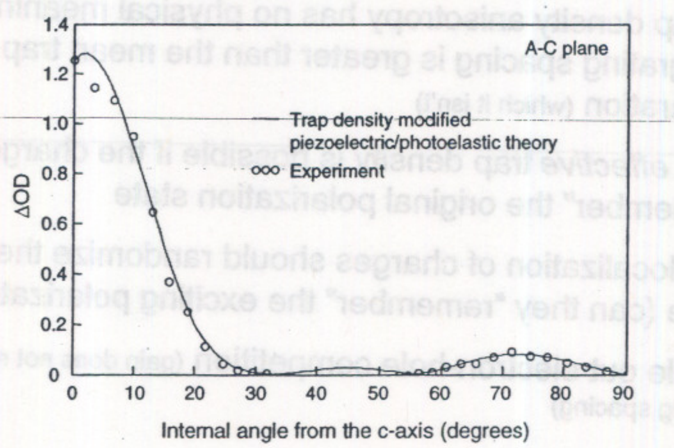
Effective trap density variations?



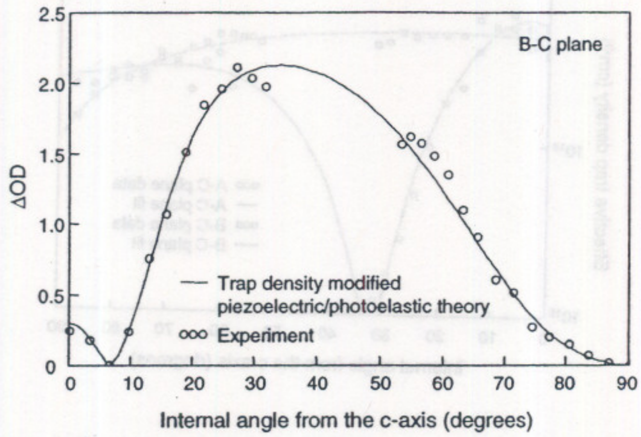
$$N_{A(AC)} = -9.09\times10^{12}\theta^6 + 3.03\times10^{15}\theta^5 - 3.85\times10^{17}\theta^4 + 2.26\times10^{19}\theta^3 - 5.67\times10^{20}\theta^2 + 3.21\times10^{21}\theta + 5\times10^{22}$$

$$N_{A(BC)} = -6\times10^{16}\theta^3 + 1\times10^{20}\theta + 4.42\times10^{22}$$

Theory modified for apparent trap density variations



Theory modified for apparent trap density variations



Discussion

- Trap density anisotropy has no physical meaning unless the grating spacing is greater than the mean trap separation (which it isn't)
- An *effective* trap density is possible if the charges "remember" the original polarization state
- Delocalization of charges should randomize the charge state (can they "remember" the exciting polarization?)
- Rule out electron-hole competition (gain does not reverse with grating spacing)

Summary

- High gain confirmed in off-axis geometries for $Fe:KNbO_3$
- Mismatch between theory and experiment for mid-range crystal angles, especially for the a-c plane
- Large apparent variation in the effective trap density with crystal angle
- Modified theory gives a good fit to experimental data
- Mechanism for trap density anisotropy is unclear